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Wind Energy Program
Programme d'énergie éolienne

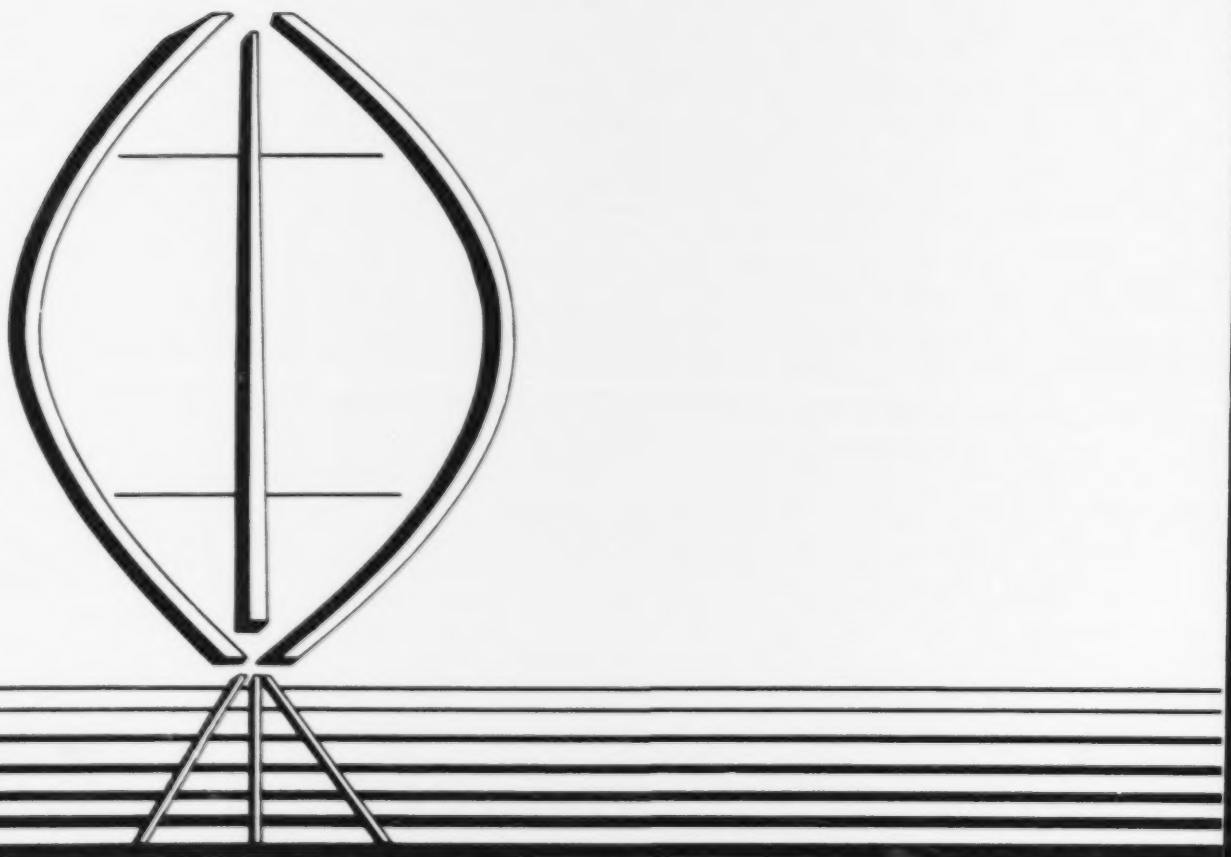
TM-WE-030

Technical Memorandum

Effects of Wind Speed Sampling and Averaging Intervals on Accuracy of Wind Energy Estimates

Atlantic Wind Test Site

December 1985



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EFFECTS OF WIND SPEED SAMPLING AND AVERAGING INTERVALS ON ACCURACY OF WIND ENERGY ESTIMATES

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SUMMARY

Wind turbine site assessment requires prediction of wind energy from historical records or measurements of wind velocity. The complexity, cost, and reliability of wind speed measurements are dependent on the frequency and duration required, and on the nature of the preprocessing needed prior to recording.

An extensive data bank of wind speed measurements was recorded on the Atlantic Wind Test Site at 1-s intervals for over 60 d. Wind speed histograms and duration curves were constructed from this data set for several "snapshot" intervals and several averaging periods. Energy and turbulence parameters were computed for the various sampling and averaging intervals and compared to corresponding parameters for the complete data set. Histogram and energy parameter calculations were repeated for a subset of data within the operating range of typical wind energy conversion systems (WECS).

The results indicated that, for the total data set, "snapshot" sampling intervals up to 15 min resulted in energy errors of less than 1%; however, the same data averaged over periods of greater than 1 min resulted in energy errors of more than 4%. For the AWTS data set used the gross assumption of Rayleigh distribution resulted in an error in predicted wind energy of over 35%. Turbulence parameters showed similar trends. For the WECS operating range subset, energy parameter errors were less than 1% for snapshot intervals up to 5 min, but between 2% and 4.5% for the 15-min snapshot interval and for all averaging periods.

RÉSUMÉ

Pour l'évaluation d'un site de turbine éolienne, il faut des prévisions de l'énergie éolienne basées sur des enregistrements historiques ou des mesures de la vitesse du vent. La complexité, le coût et la fiabilité des mesures de la vitesse du vent sont fonction de la fréquence et de la durée requises, de même que de la nature du traitement préliminaire requis avant l'enregistrement.

Au Centre d'essais éoliens de l'Atlantique on a créé une vaste banque de données de mesures de la vitesse du vent effectuées à des intervalles de 2 s pendant plus de 60 d. Des histogrammes de la vitesse du vent et des courbes de durée ont été construits à partir de cette banque de données pour plusieurs intervalles d'"analyse sélective" et plusieurs périodes de calcul de la moyenne. Les paramètres d'énergie et de turbulence ont été calculés pour les différents intervalles d'échantillonnage et de calcul de la moyenne, et ils ont été comparés aux paramètres correspondants de l'ensemble de données complet. La construction de l'histogramme et le calcul des paramètres d'énergie ont été répétés pour un sous-ensemble de données appartenant à la plage de fonctionnement de systèmes de conversion de l'énergie éolienne (SCEE) types.

Les résultats ont indiqué que pour l'ensemble de données complet, les intervalles d'échantillonnage pour "analyse sélective" allant jusqu'à 15 min ont donné lieu à des erreurs sur le paramètre d'énergie de moins de 1 %; toutefois, les mêmes données avec une moyenne calculée sur des périodes dépassant 1 min ont donné des erreurs sur le paramètre d'énergie dépassant 4 %. Pour l'ensemble de données de l'AWTS utilisé, l'hypothèse grossière d'une distribution de Rayleigh a donné lieu à une erreur sur l'énergie éolienne prévue de plus de 35 %. Les paramètres de turbulence ont présenté des tendances similaires. Dans le cas du sous-ensemble de la plage de fonctionnement des SCEE, les erreurs sur le paramètre d'énergie étaient inférieures à 1 % pour les intervalles d'analyse sélective allant jusqu'à 5 min, mais comprises entre 2 % et 4,5 % pour l'intervalle d'analyse sélective de 15 min, quelle que soit la période de calcul de la moyenne.

EFFECTS OF WIND SPEED SAMPLING AND AVERAGING INTERVALS ON ACCURACY OF WIND ENERGY ESTIMATES

C. Brothers and H. Arthur

INTRODUCTION

The assessment of a potential site for wind energy development requires reasonably accurate prediction of the wind energy available at that site. To make this prediction the wind speed must be monitored or recorded over a period of time.

The equipment available to record the required data varies in the complexity of data acquisition capability, cost, and reliability of operation.

METHODS OF OBSERVATION

The Atlantic Wind Test Site (AWTS) has available a bank of 1-s data which can be manipulated to simulate various equipment and techniques. In an effort to evaluate different techniques of data acquisition the AWTS was requested to perform analysis on 60 d of 1-s wind speed data to compare accuracy of various methods. The object and statement of work of the project are outlined in Appendix A.

METHODS OF ANALYSIS

The AWTS, as part of a project being conducted for the Atmospheric Environment Service to carry out a comparison of different types of anemometers, records wind speed once per second on a continuous basis.

For a 60-d time period in early 1985 the 1-s data from an AES model U2A anemometer was analyzed as requested by the National Research Council to obtain histograms (using 0.5 m/s bin widths) for the following time periods:

1. using 1-s data then binning
2. using every 10th point and then binning
3. using every 60th point and then binning
4. using every 300th point and then binning
5. using every 900th point and then binning
6. using 10-s average and then binning
7. using 1-min average and then binning

8. using 5-min average and then binning
9. using 15-min average and then binning

In addition, turbulence calculations were made on the first three histograms above.

RESULTS

Histograms and probability distributions for the nine methods are shown in Appendix C along with some statistical analysis of correlations between the histograms.

According to the correlation matrix there is very good agreement between all methods of calculation and the 1-s data used as the standard. Correlation ranges from 99.986% for every 10th point to 97.026% for 15-min averages (see Appendix B).

A visual comparison of the histograms and probability distribution can be done by overlaying the originals individually and observing any discrepancy. The slight differences are expected given the various methods.

Comparing binned 1-s data with binned data from the 10th, 60th, 300th, and 900th point, we see the same general distribution with increasing amounts of individual point scatter as the sample time increases.

Comparing the 10-s, 1-min, 5-min, and 15-min averages with the 1-s data in a similar manner again shows expected differences. On these histograms the distribution tends to eliminate the wind speeds of low duration mostly at the lower and higher end of the range. Wind speeds with a higher probability of occurring tend to increase in frequency as the time period lengthens. This could be taken to an extreme of one reading scanning some 5 600 000 s occurring at the average wind speed (7.6 m/s in this instance).

In addition to plotting the histograms and probability distributions and calculating the correlation between the various methods, calculations were also made on energy availability (see Appendix D). The purpose of most wind site evaluations is to determine the viability of a WECS installation. The methods that are being considered for data acquisition in site assessment should be based on their accuracy of predicting actual wind energy availability at that site. Plotting of histograms is a very subjective way of evaluating methods of analysis. Calculating the energy availability provides a much more objective evaluation of data.

The energy availability of Appendix E shows quite good agreement of total energy available using each of the methods indicated. Using 1-s data as reference, the accuracy of predicted energy is within 2% of each of the instantaneous readings. The slight fluctuation is probably due to the scatter evident on the histogram. For the averaged wind speeds the energy availability reduces as the average time period increases due to the tendency of the averaging to eliminate wind speeds of short duration at higher speeds where the energy is significantly higher. The projected energy available for 15-min averages is still within 5% of 1-s data. It is interesting to note that if we took the average wind speed of 7.6 m/s, assumed Rayleigh distribution and calculated energy availability, we would underestimate energy availability by over 35%.

In a subsequent exploration wind speed histograms and the energy availability parameter were calculated using only data from within a typical WECS operating range of 5 to 20 m/s. All data both above and below these limits were discarded, and the remaining subset was used to form truncated histograms (Appendix D). The energy availability parameters for the WECS range data subset are shown in the second column of Appendix E for the same selection of sampling intervals and averaging periods (1, 10, 60, 300, 900 s) as used for the complete data set. Errors, relative to the 1-s data, were less than 1% for sampling intervals of 10, 60, and 300 s; however, errors increased from 2% to 4½% for the 900-s sampling interval and all four averaging periods. Nevertheless, other uncertainties in WECS energy estimation for a specific site may well exceed 5%. Thus it appears even infrequent sampling will provide adequate accuracy. The importance of the total duration of measurement has not been addressed in this study, but is believed to be significant in view of weather system periodicity and seasonal variations.

The turbulence was calculated using data for the 1-s data as well as the 10th and 60th data points for a variety of wind speeds.

In the turbulence calculations the mean wind speeds agree with the 1-s values within 1% for the 10th point and within 3% for the 60th point. Turbulence, which is simply the standard deviation divided by the mean wind speed, for the 10th point increases to about 4% higher than 1-s readings while for th 60th point the turbulence is as much as 30% higher. The tables in Appendix F illustrate the relationship between turbulence level, mean wind speed, and sampling intervals. This variation in turbulence compared to 1-s data, although not excessive, leads to the increased scatter one would expect in power resulting from the reduced number of samples. The increased scatter may also be the result of fluctuation in wind speed over time rather than actual turbulence.

CONCLUSIONS

The nine histograms that were plotted correlate to 3%. Calculating energy available using the nine histograms predicts energy available to within 5%. Usual fluctuations of histograms for a given site from one year to the next usually exceed this variation. Recommending appropriate scan rates is difficult when the difference in various methods is so slight. However, depending on the information required and the test period available for testing, some methods would have preference over others.

Recording 1-s data is obviously the best technique to provide an accurate assessment of wind speeds, turbulence, gust intensities, and other parameters.

Recording instantaneous wind speed on a regular but increasingly infrequent basis will provide a good estimate of energy available over a period of time. IF the test period is relatively short, however, there is an increasing chance that the infrequency of the sampling will affect the conclusions. Also, turbulence and high wind speeds can be predicted with less confidence. Average readings, as indicated earlier, tend to remove periods of low durations and would give unreliable indications of gust intensities. Turbulence also cannot be calculated using average readings.

In conclusion, if a site can be monitored for a considerable period and a simple prediction of annual energy available is required, any of the nine methods can be used with acceptable accuracy. The factors determining which type of data to collect should be based on cost and reliability of equipment available. If more specialized information is required, such as turbulence or gust measurement, a 1-s histogram may be necessary.

APPENDIX A. OBJECT AND STATEMENT OF WORK

INTRODUCTION

Wind measurement is an important aspect of the wind energy program. Accurate site assessment of potential wind turbine installations is essential to ensure the economic predictions and viability of a site. To do this, NRC has a program of data acquisition at these potential and existing wind turbine sites. The amount of data now gathered is substantial. With more sites being monitored all the time and the added problem of poor reliability of the existing equipment now installed, NRC has decided to update the equipment and methods of data gathering.

The amount of data to analyse is very dependent on the scan rate and type of data taken. The purpose of this study is to address the question of scan rate and instantaneous or average readings. Using the same data set a comparison will be done using various methods of data acquisition. Each method will then be analyzed, (i.e., histograms, etc.) and then determined for acceptability. From this we hope to find out what is the minimum amount of data for an accurate site assessment.

STATEMENT OF WORK

It is proposed that at least two months of 1-s wind data will be used for the test. The histograms developed for each method will have 0.5 m/s width bins. The following histograms will be calculated:

1. using 1-s data then binning
2. using every 10th point and then binning
3. using every 60th point and then binning
4. using every 300th point and then binning
5. using every 900th point and then binning
6. using 10-s average and then binning
7. using 1-min average and then binning
8. using 5-min average and then binning
9. using 15-min average and then binning

Turbulence will also be calculated using data sets from the first three histograms above. Five turbulence calculations should be taken over the two month data set using each time less than 1 h of data. Mean wind speeds are also important in turbulence calculations and should be stated for each case. Other calculations to show degradation in the data for comparison purposes may be proposed. A final report will then be written highlighting the pitfalls of each type of data gathering and recommending scan rates that are acceptable and whether instantaneous or average readings can be employed with equal accuracy.

APPENDIX B. CORRELATION MATRIX

Correlation Matrix

SUMMARY STATISTICS
ON DATA SET:

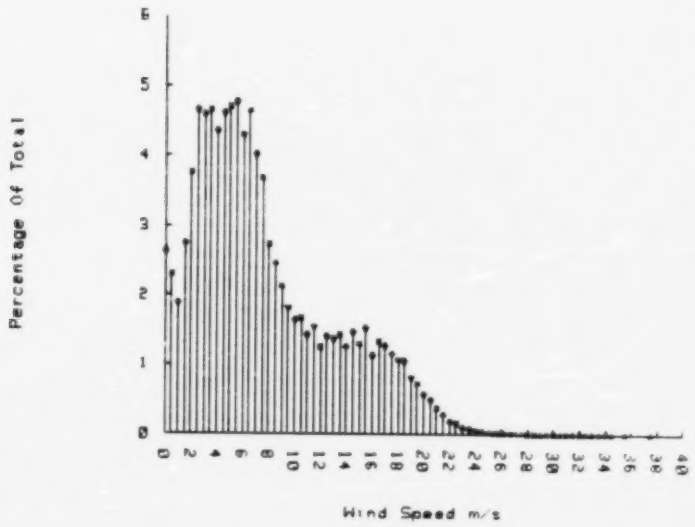
	1Sec POINT	10th POINT	60th POINT	300 POINT	900 POINT	10Sec AVE.
BIN NUMBER	-.8540771	-.8539914	-.8546528	-.8515987	-.8422224	-.8456058
1Sec POINT		.9998601	.9989928	.9960383	.9901110	.9968514
10th POINT			.9991318	.9956842	.9898052	.9963406
60th POINT				.9961721	.9908058	.9963045
300 POINT					.9932724	.9936091
900 POINT						.9873030

	1Min AVE.	5Min AVE.	15Min AVE.
BIN NUMBER	-.8339953	-.8181210	-.8102714
1Sec POINT	.9911717	.9803571	.9702619
10th POINT	.9911446	.9802962	.9707230
60th POINT	.9906884	.9791813	.9703326
300 POINT	.9878261	.9747788	.9664784
900 POINT	.9819294	.9713701	.9608361
10Sec AVE.	.9973949	.9879102	.9779795
1Min AVE.		.9940766	.9836742
5Min AVE.			.9904824

APPENDIX C. WIND SPEED HISTOGRAMS AND DURATION PLOTS

Wind Measurement Study
Number Of Data Points Is 5601610

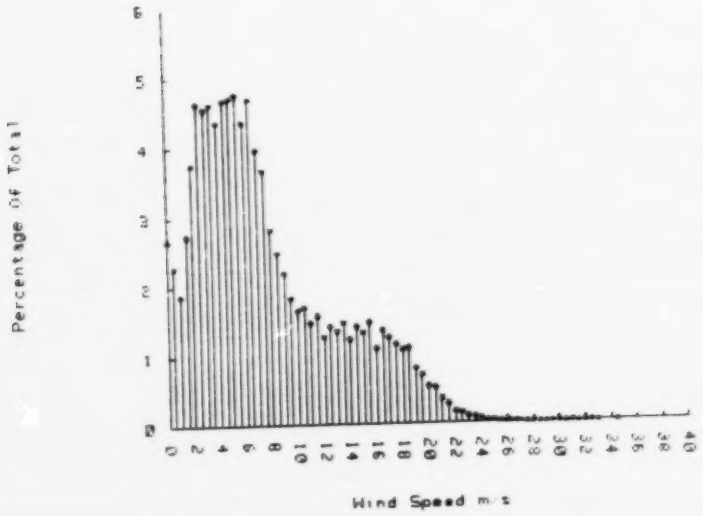
BINNED 1 SECOND DATA



Bin Number	% Total	Bin Number	% Total
0	2.636		
.5	2.3007	20.5	.4996
1	1.8966	21	.3842
1.5	2.7556	21.5	.2906
2	3.7708	22	.1915
2.5	4.6684	22.5	.1284
3	4.6057	23	.1064
3.5	4.6583	23.5	.0828
4	4.364	24	.0516
4.5	4.6201	24.5	.0436
5	4.6976	25	.0333
5.5	4.777	25.5	.0252
6	4.3102	26	.0217
6.5	4.6525	26.5	.0173
7	4.0262	27	.0124
7.5	3.6853	27.5	.0109
8	2.7364	28	.0073
8.5	2.4692	28.5	.006
9	2.1327	29	.0045
9.5	1.821	29.5	.003
10	1.651	30	.0017
10.5	1.6653	30.5	.0016
11	1.4287	31	.0008
11.5	1.5422	31.5	.0005
12	1.249	32	.0003
12.5	1.4120	32.5	.0002
13	1.3761	33	.0001
13.5	1.4298	33.5	.0001
14	1.2619	34	.0001
14.5	1.4732	34.5	.0001
15	1.3009	35	0
15.5	1.5293	35.5	0
16	1.1359	36	0
16.5	1.3306	36.5	0
17	1.2699	37	0
17.5	1.1615	37.5	0
18	1.0661	38	0
18.5	1.0349	38.5	0
19	.8887	39	0
19.5	.7241	39.5	0
20	.5889	40	0

Wind Measurement Study
Number Of Data Points In Set=282

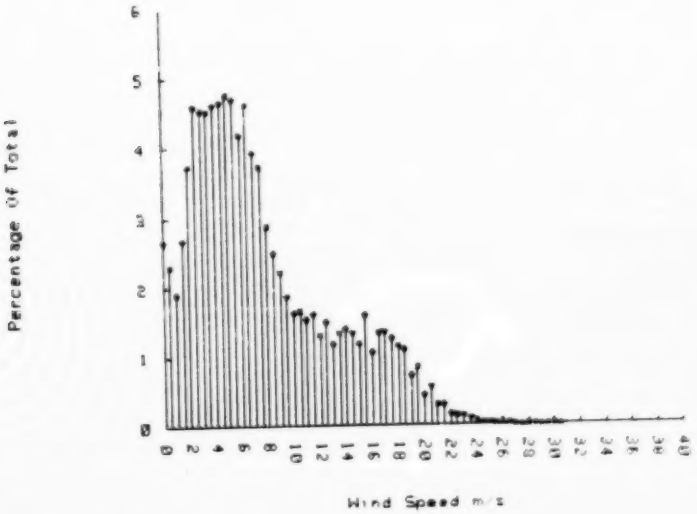
10th DATA POINT BINNED



Bin Number	% Total	Bin Number	% Total
0	2.6679	20.5	.523
.5	2.2862	21	.3614
1	1.8757	21.5	.2805
1.5	2.7381	22	.1609
2	3.7571	22.5	.1554
2.5	4.647	23	.1065
3	4.5604	23.5	.0873
3.5	4.6134	24	.0584
4	4.3732	24.5	.0426
4.5	4.6834	25	.0368
5	4.7096	25.5	.0231
5.5	4.7645	26	.0218
6	4.3633	26.5	.0157
6.5	4.692	27	.0123
7	3.9718	27.5	.0093
7.5	3.6647	28	.0069
8	2.8113	28.5	.0049
8.5	2.4893	29	.0049
9	2.192	29.5	.004
9.5	1.8288	30	.0012
10	1.6534	30.5	.0025
10.5	1.6962	31	.0002
11	1.4715	31.5	.0005
11.5	1.5751	32	.0004
12	1.2652	32.5	.0002
12.5	1.4185	33	.0002
13	1.3423	33.5	0
13.5	1.4623	34	0
14	1.2374	34.5	.0002
14.5	1.4065	35	0
15	1.3254	35.5	0
15.5	1.4649	36	0
16	1.0924	36.5	0
16.5	1.3513	37	0
17	1.2483	37.5	0
17.5	1.1491	38	0
18	1.0776	38.5	0
18.5	1.0958	39	0
19	.8042	39.5	0
19.5	.7046	40	0
20	.5393		

Wind Measurement Study
Number Of Data Points Is 94634

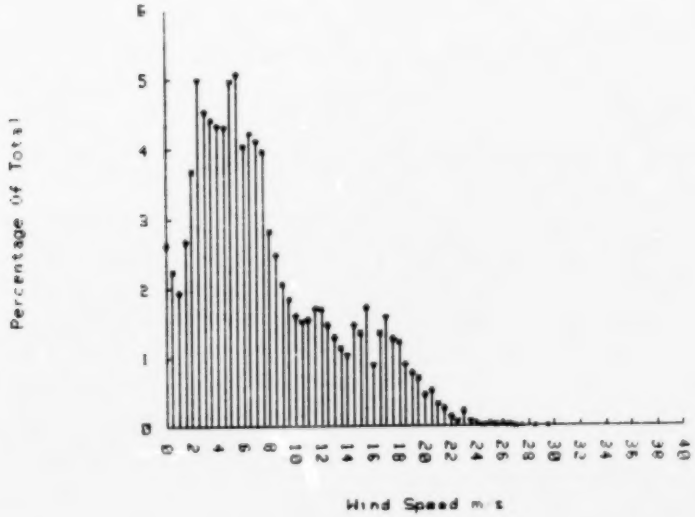
60th DATA POINT BINNED



Bin Number	% Total	Bin Number	% Total
0	2.652		
.5	2.3083	20.5	.5513
1	1.9106	21	.2989
1.5	2.6889	21.5	.3042
2	3.7398	22	.1637
2.5	4.6006	22.5	.1479
3	4.5446	23	.1362
3.5	4.5224	23.5	.0961
4	4.6291	24	.0623
4.5	4.6587	24.5	.0338
5	4.7611	25	.0336
5.5	4.703	25.5	.0243
6	4.1887	26	.019
6.5	4.628	26.5	.018
7	3.9363	27	.0095
7.5	3.725	27.5	.0074
8	2.8727	28	.0074
8.5	2.4999	28.5	.0074
9	2.2158	29	.0063
9.5	1.8694	29.5	.0032
10	1.6349	30	.0011
10.5	1.6465	30.5	.0011
11	1.5293	31	0
11.5	1.6117	31.5	0
12	1.3012	32	0
12.5	1.4871	32.5	0
13	1.1734	33	0
13.5	1.3244	33.5	0
14	1.3952	34	0
14.5	1.3244	34.5	0
15	1.1818	35	0
15.5	1.5948	35.5	0
16	1.0551	36	0
16.5	1.3286	36.5	0
17	1.3424	37	0
17.5	1.2526	37.5	0
18	1.1406	38	0
18.5	1.0899	38.5	0
19	.7224	39	0
19.5	.8417	39.5	0
20	.4425	40	0

Wind Measurement Study
Number Of Data Points Is 10910

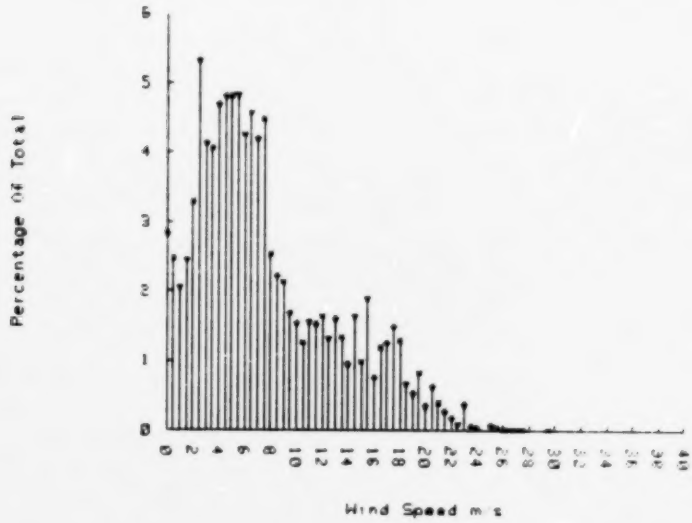
300th DATA POINT BINNED



Bin Number	% Total	Bin Number	% Total
0	2.623		
.5	2.2422	20.5	.5182
1	1.9513	21	.3279
1.5	2.6811	21.5	.2644
2	3.6859	22	.1428
2.5	4.9921	22.5	.074
3	4.5426	23	.2168
3.5	4.4262	23.5	.074
4	4.3416	24	.0317
4.5	4.331	24.5	.0159
5	4.9709	25	.0476
5.5	5.0767	25.5	.0264
6	4.0455	26	.0317
6.5	4.2359	26.5	.0212
7	4.1248	27	.0053
7.5	3.9714	27.5	.0106
8	2.8133	28	0
8.5	2.4907	28.5	.0053
9	2.0624	29	0
9.5	1.8456	29.5	.0053
10	1.6129	30	0
10.5	1.523	30.5	0
11	1.5442	31	0
11.5	1.7187	31.5	0
12	1.6975	32	0
12.5	1.4754	32.5	0
13	1.2956	33	0
13.5	1.1317	33.5	0
14	1.0259	34	0
14.5	1.4754	34.5	0
15	1.3538	35	0
15.5	1.7345	35.5	0
16	.8884	36	0
16.5	1.3538	36.5	0
17	1.5812	37	0
17.5	1.2692	37.5	0
18	1.2216	38	0
18.5	.9843	38.5	0
19	.7721	39	0
19.5	.6928	39.5	0
20	.4548	40	0

Wind Measurement Study
Number Of Data Points Is 6271

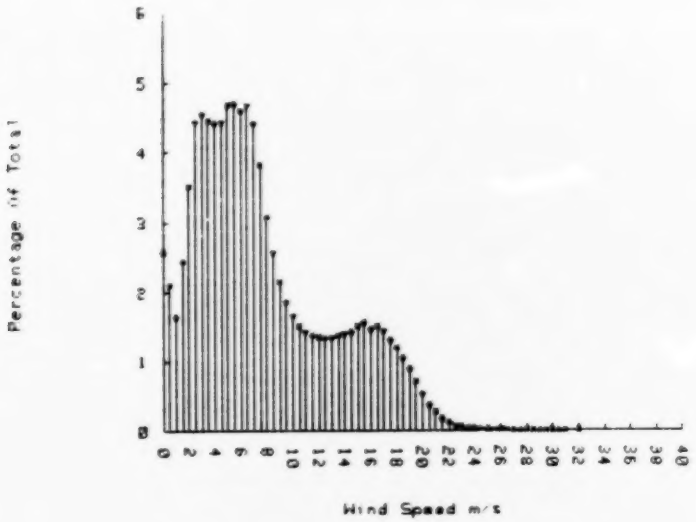
500th DATA POINT BINNED



Bin Number	% Total	Bin Number	% Total
0	2.8385		
.5	2.4876	20.5	.6379
1	2.0571	21	.3987
1.5	2.4557	21.5	.287
2	3.3009	22	.1914
2.5	5.3421	22.5	.0957
3	4.1461	23	.3827
3.5	4.0663	23.5	.0638
4	4.7042	24	.0319
4.5	4.8158	24.5	0
5	4.8158	25	.0797
5.5	4.8318	25.5	.0479
6	4.2577	26	.0159
6.5	4.5766	26.5	.0159
7	4.2099	27	.0159
7.5	4.4809	27.5	.0159
8	2.5355	28	0
8.5	2.2325	28.5	0
9	2.1368	29	0
9.5	1.6903	29.5	.0159
10	1.5468	30	0
10.5	1.2598	30.5	0
11	1.5627	31	0
11.5	1.5309	31.5	0
12	1.6425	32	0
12.5	1.3236	32.5	0
13	1.6106	33	0
13.5	1.3395	33.5	0
14	.9568	34	0
14.5	1.6425	34.5	0
15	.9887	35	0
15.5	1.8976	35.5	0
16	.7654	36	0
16.5	1.196	36.5	0
17	1.2598	37	0
17.5	1.499	37.5	0
18	1.2917	38	0
18.5	.6697	38.5	0
19	.5422	39	0
19.5	.8292	39.5	0
20	.3668	40	0

Wind Measurement Study
Number Of Data Points Is 568282

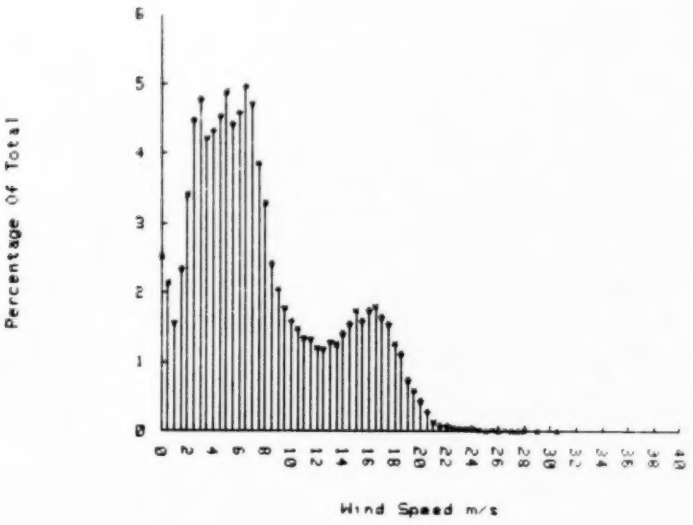
10 SECOND AVERAGES BINNED



Bin Number	% Total	Bin Number	% Total
0	2.5808		
.5	2.1062	20.5	.3861
1	1.6525	21	.2833
1.5	2.4486	21.5	.1767
2	3.5233	22	.1304
2.5	4.4527	22.5	.0743
3	4.5634	23	.0614
3.5	4.4603	23.5	.0421
4	4.429	24	.0354
4.5	4.4349	24.5	.0306
5	4.6848	25	.0216
5.5	4.7084	25.5	.0137
6	4.6002	26	.0144
6.5	4.6757	26.5	.0118
7	4.427	27	.0088
7.5	3.8238	27.5	.0048
8	3.0835	28	.0046
8.5	2.5727	28.5	.003
9	2.1565	29	.0023
9.5	1.8651	29.5	.0009
10	1.6596	30	.0002
10.5	1.5117	30.5	.0004
11	1.425	31	.0002
11.5	1.3792	31.5	0
12	1.3493	32	.0002
12.5	1.3418	32.5	0
13	1.3437	33	0
13.5	1.3791	33.5	0
14	1.4046	34	0
14.5	1.4275	34.5	0
15	1.5091	35	0
15.5	1.564	35.5	0
16	1.466	36	0
16.5	1.5177	36.5	0
17	1.4424	37	0
17.5	1.3134	37.5	0
18	1.2017	38	0
18.5	1.0586	38.5	0
19	.8915	39	0
19.5	.7188	39.5	0
20	.5379	40	0

Wind Measurement Study
Number Of Data Points Is 94634

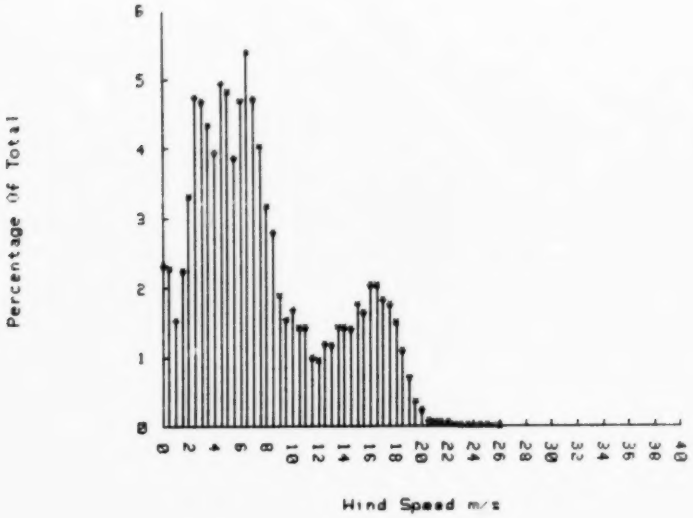
1 MINUTE AVERAGES BINNED



Bin Number	% Total	Bin Number	% Total
0	2.5189		
.5	2.1397	20.5	.2904
1	1.5631	21	.1331
1.5	2.3478	21.5	.0792
2	3.4113	22	.0792
2.5	4.4844	22.5	.0444
3	4.7801	23	.0359
3.5	4.2182	23.5	.0338
4	4.3344	24	.0306
4.5	4.5414	24.5	.0158
5	4.8773	25	.0095
5.5	4.4295	25.5	.0158
6	4.5911	26	.0074
6.5	4.9601	26.5	.0106
7	4.7146	27	.0011
7.5	3.8592	27.5	.0011
8	3.2931	28	.0021
8.5	2.4239	28.5	0
9	2.0542	29	.0032
9.5	1.7796	29.5	0
10	1.5969	30	0
10.5	1.4807	30.5	.0011
11	1.3445	31	0
11.5	1.3233	31.5	0
12	1.204	32	0
12.5	1.1871	32.5	0
13	1.2853	33	0
13.5	1.2526	33.5	0
14	1.4121	34	0
14.5	1.5483	34.5	0
15	1.7416	35	0
15.5	1.5969	35.5	0
16	1.7543	36	0
16.5	1.8007	36.5	0
17	1.655	37	0
17.5	1.5504	37.5	0
18	1.261	38	0
18.5	1.1121	38.5	0
19	.7435	39	0
19.5	.5862	39.5	0
20	.4394	40	0

Wind Measurement Study
Number Of Data Points Is 18910

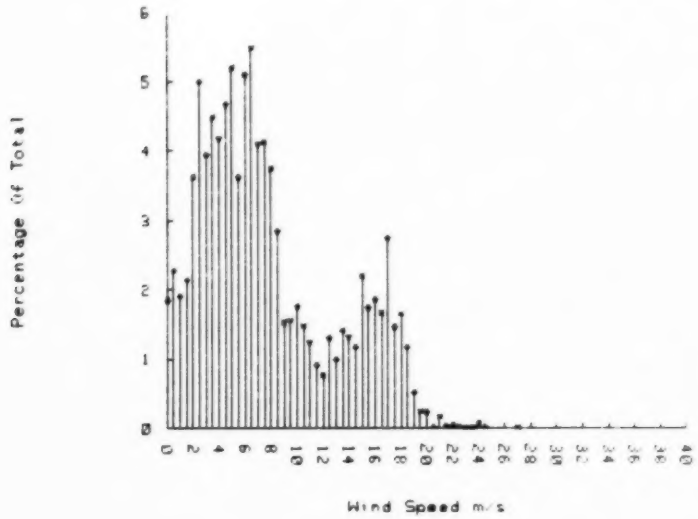
5 MINUTE AVERAGES BINNED



Bin Number	% Total	Bin Number	% Total
0	2.3268		
.5	2.2792	20.5	.0846
1	1.5389	21	.074
1.5	2.2422	21.5	.0582
2	3.3104	22	.0687
2.5	4.7488	22.5	.037
3	4.6854	23	.0264
3.5	4.3416	23.5	.0212
4	3.945	24	.0106
4.5	4.9498	24.5	.0264
5	4.8176	25	.0264
5.5	3.871	25.5	.0106
6	4.6959	26	.0053
6.5	5.3993	26.5	0
7	4.7171	27	0
7.5	4.0349	27.5	0
8	3.1782	28	0
8.5	2.7975	28.5	0
9	1.8985	29	0
9.5	1.5547	29.5	0
10	1.6869	30	0
10.5	1.4331	30.5	0
11	1.4331	31	0
11.5	.9889	31.5	0
12	.9572	32	0
12.5	1.1951	32.5	0
13	1.174	33	0
13.5	1.4437	33.5	0
14	1.4331	34	0
14.5	1.412	34.5	0
15	1.7768	35	0
15.5	1.6499	35.5	0
16	2.0518	36	0
16.5	2.0518	36.5	0
17	1.835	37	0
17.5	1.7663	37.5	0
18	1.5124	38	0
18.5	1.0999	38.5	0
19	.7086	39	0
19.5	.3702	39.5	0
20	.238	40	0

Wind Measurement Study
Number Of Data Points Is 6471

15 MINUTE AVERAGES BINNED

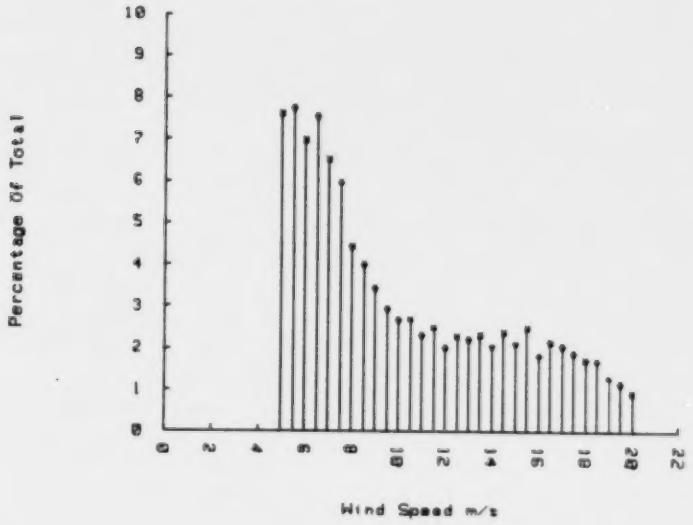


Bin Number	% Total	Bin Number	% Total
0	1.8498		
.5	2.2883	20.5	.0319
1	1.9136	21	.1754
1.5	2.1520	21.5	.0478
2	3.6358	22	.0478
2.5	5.0072	22.5	.0319
3	3.9547	23	.0159
3.5	4.4809	23.5	.0159
4	4.178	24	.0797
4.5	4.6082	24.5	.0319
5	5.1985	25	0
5.5	3.6358	25.5	0
6	5.1029	26	0
6.5	5.4856	26.5	0
7	4.0982	27	.0159
7.5	4.1301	27.5	0
8	3.7474	28	0
8.5	2.8544	28.5	0
9	1.5309	29	0
9.5	1.5627	29.5	0
10	1.7701	30	0
10.5	1.403	30.5	0
11	1.2438	31	0
11.5	.9249	31.5	0
12	.7814	32	0
12.5	1.3076	32.5	0
13	1.0046	33	0
13.5	1.4192	33.5	0
14	1.3236	34	0
14.5	1.18	34.5	0
15	2.2006	35	0
15.5	1.7541	35.5	0
16	1.8657	36	0
16.5	1.6744	36.5	0
17	2.7587	37	0
17.5	1.4671	37.5	0
18	1.6584	38	0
18.5	1.18	38.5	0
19	.5262	39	0
19.5	.2551	39.5	0
20	.2392	40	0

APPENDIX D. WIND SPEED HISTOGRAMS (WECS OPERATING RANGE)

Wind Measurement Study
Energy Intensity = 1642.42597837

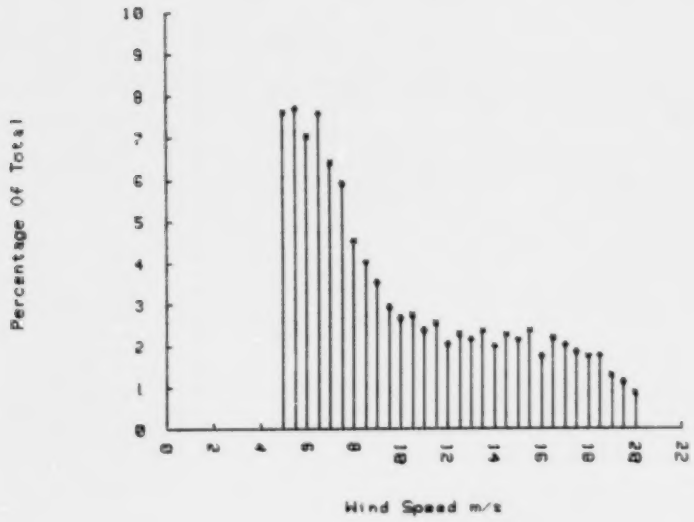
BINNED 1 SECOND DATA



Bin Number	Bin Count	% Total
5	263142	7.6061
5.5	267591	7.7347
6	241438	6.9788
6.5	260614	7.533
7	225532	6.519
7.5	206437	5.9671
8	153284	4.4307
8.5	138313	3.9979
9	119466	3.4532
9.5	102085	2.9485
10	92484	2.6732
10.5	93282	2.6963
11	80832	2.3133
11.5	86398	2.4971
12	69965	2.0223
12.5	79141	2.2876
13	77084	2.2281
13.5	80098	2.315
14	70609	2.0433
14.5	82525	2.3854
15	72869	2.1063
15.5	85664	2.4761
16	63627	1.8391
16.5	74534	2.1544
17	71135	2.0562
17.5	65063	1.8806
18	59719	1.7262
18.5	59098	1.708
19	45301	1.3094
19.5	40563	1.1725
20	32541	.9406

Wind Measurement Study
Energy Intensity = 1630.14419749

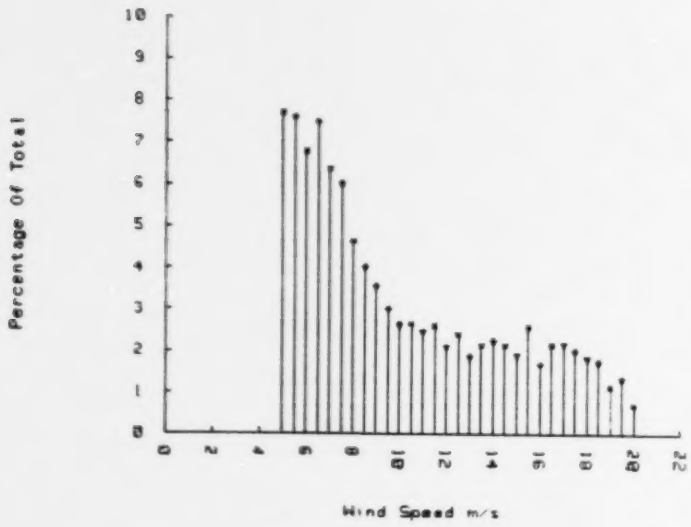
10th DATA POINT BINNED



Bin Number	Bin Count	% Total
5	26764	7.6123
5.5	27076	7.701
6	24796	7.0526
6.5	26664	7.5839
7	22571	6.4197
7.5	20826	5.9234
8	15976	4.5439
8.5	14146	4.0234
9	12457	3.5431
9.5	10393	2.956
10	9396	2.6724
10.5	9639	2.7416
11	8362	2.3783
11.5	8951	2.5459
12	7190	2.045
12.5	8061	2.2927
13	7628	2.1696
13.5	8310	2.3636
14	7032	2.0001
14.5	7993	2.2734
15	7532	2.1423
15.5	8325	2.3678
16	6208	1.7657
16.5	7679	2.1841
17	7094	2.0177
17.5	6530	1.8573
18	6124	1.7418
18.5	6227	1.7711
19	4570	1.2998
19.5	4004	1.1388
20	3065	.8718

Wind Measurement Study
Energy Intensity = 1640.19359848

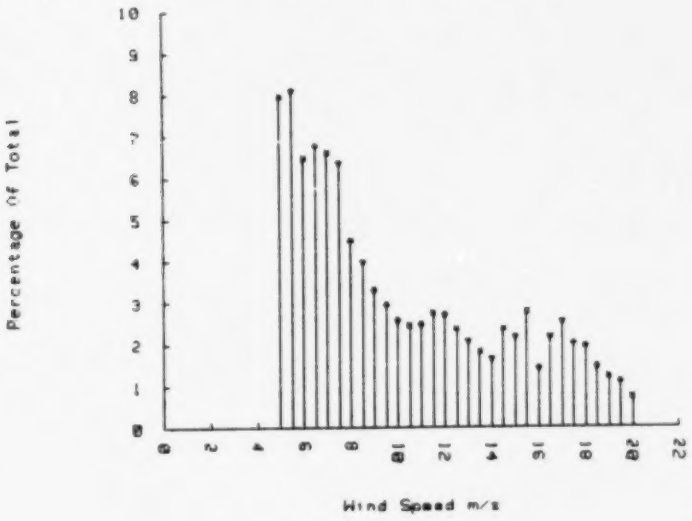
60th DATA POINT BINNED



Bin Number	Bin Count	% Total
5	4508	7.7015
5.5	4453	7.6075
6	3966	6.7755
6.5	4382	7.4862
7	3727	6.3672
7.5	3527	6.0256
8	2720	4.6469
8.5	2367	4.0438
9	2098	3.5842
9.5	1770	3.0239
10	1549	2.6466
10.5	1559	2.6634
11	1448	2.4738
11.5	1526	2.607
12	1232	2.1048
12.5	1408	2.4054
13	1111	1.898
13.5	1254	2.1423
14	1321	2.2568
14.5	1254	2.1423
15	1119	1.9117
15.5	1510	2.5797
16	999	1.7067
16.5	1258	2.1492
17	1271	2.1714
17.5	1186	2.0262
18	1080	1.8451
18.5	1032	1.7631
19	684	1.1686
19.5	797	1.3616
20	419	.7158

Wind Measurement Study
Energy Intensity = 1630.63222986

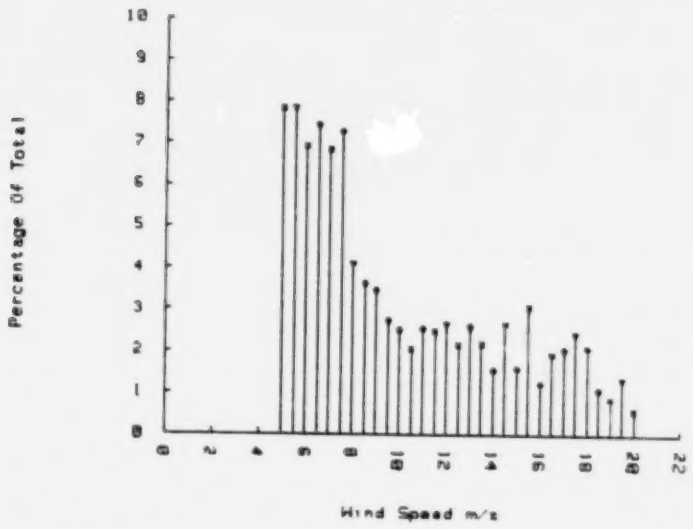
300th DATA POINT BINNED



Bin Number	Bin Count	% Total
5	940	7.9708
5.5	960	8.1404
6	765	6.4869
6.5	801	6.7922
7	780	6.6141
7.5	751	6.3682
8	532	4.5112
8.5	471	3.9939
9	390	3.307
9.5	349	2.9594
10	305	2.5863
10.5	288	2.4421
11	292	2.476
11.5	325	2.7559
12	321	2.722
12.5	279	2.3658
13	245	2.0775
13.5	214	1.8146
14	194	1.645
14.5	279	2.3658
15	256	2.1708
15.5	328	2.7813
16	168	1.4246
16.5	256	2.1708
17	299	2.5354
17.5	240	2.0351
18	231	1.9588
18.5	171	1.45
19	146	1.238
19.5	131	1.1108
20	86	.7292

Wind Measurement Study
Energy Intensity = 1587.35968724

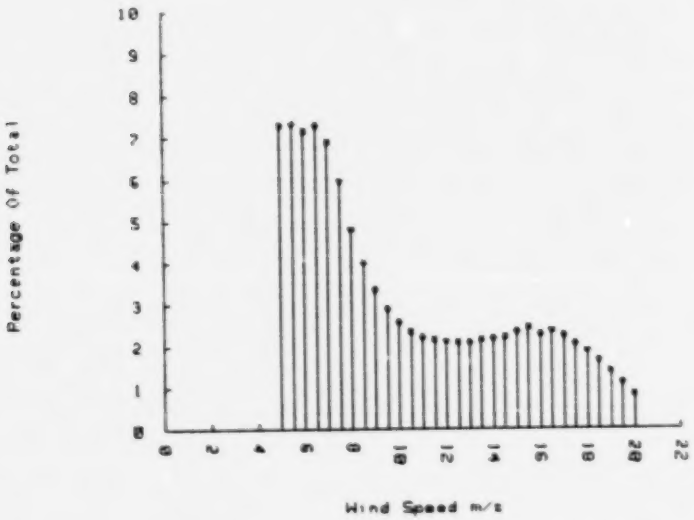
900th DATA POINT BINNED



Bin Number	Bin Count	% Total
5	302	7.832
5.5	303	7.8579
6	267	6.9243
6.5	287	7.4429
7	264	6.8465
7.5	281	7.2873
8	159	4.1234
8.5	140	3.6307
9	134	3.4751
9.5	106	2.749
10	97	2.5156
10.5	79	2.0488
11	98	2.5415
11.5	96	2.4896
12	103	2.6712
12.5	83	2.1525
13	101	2.6193
13.5	84	2.1784
14	60	1.556
14.5	103	2.6712
15	62	1.6079
15.5	119	3.0861
16	48	1.2448
16.5	75	1.945
17	79	2.0488
17.5	94	2.4378
18	81	2.1006
18.5	42	1.0892
19	34	.8817
19.5	52	1.3485
20	23	.5965

Wind Measurement Study
Energy Intensity = 1676.13653931

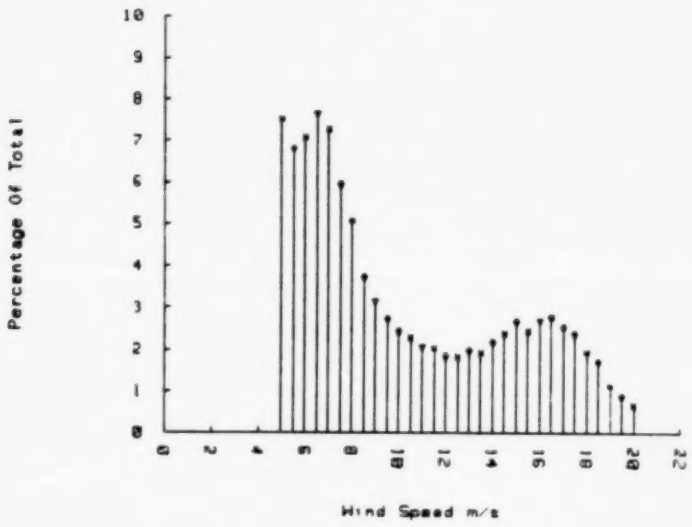
10 SECOND AVERAGES BINNED



Bin Number	Bin Count	% Total
5	26623	7.3154
5.5	26757	7.3522
6	26142	7.1832
6.5	26571	7.3011
7	25158	6.9129
7.5	21730	5.9709
8	17523	4.8149
8.5	14620	4.0173
9	12255	3.3674
9.5	10599	2.9124
10	9431	2.5914
10.5	8591	2.3606
11	8090	2.2252
11.5	7830	2.1537
12	7660	2.107
12.5	7625	2.0952
13	7636	2.0982
13.5	7837	2.1534
14	7982	2.1933
14.5	8112	2.229
15	8576	2.3565
15.5	8088	2.4422
16	8331	2.2892
16.5	8625	2.37
17	8197	2.2524
17.5	7464	2.0509
18	6829	1.8765
18.5	6016	1.6531
19	5066	1.392
19.5	4085	1.1225
20	3057	.84

Wind Measurement Study
Energy Intensity = 1696.6387419

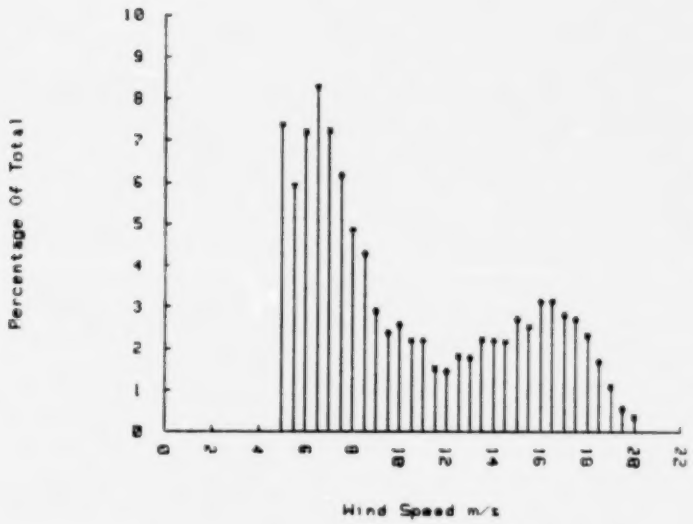
1 MINUTE AVERAGES BINNED



Bin Number	Bin Count	% Total
5	4618	7.519
5.5	4194	6.8286
6	4347	7.0777
6.5	4704	7.659
7	4464	7.2682
7.5	3654	5.9494
8	3110	5.0667
8.5	2295	3.7367
9	1945	3.1668
9.5	1685	2.7435
10	1512	2.4618
10.5	1402	2.2827
11	1273	2.0727
11.5	1253	2.0401
12	1140	1.8561
12.5	1124	1.8301
13	1217	1.9815
13.5	1186	1.931
14	1337	2.1769
14.5	1466	2.3869
15	1649	2.6849
15.5	1512	2.4618
16	1661	2.7044
16.5	1705	2.7761
17	1567	2.5514
17.5	1468	2.3902
18	1194	1.9441
18.5	1053	1.7145
19	704	1.1462
19.5	555	.9036
20	416	.6773

Wind Measurement Study
Energy Intensity = 1714.03458746

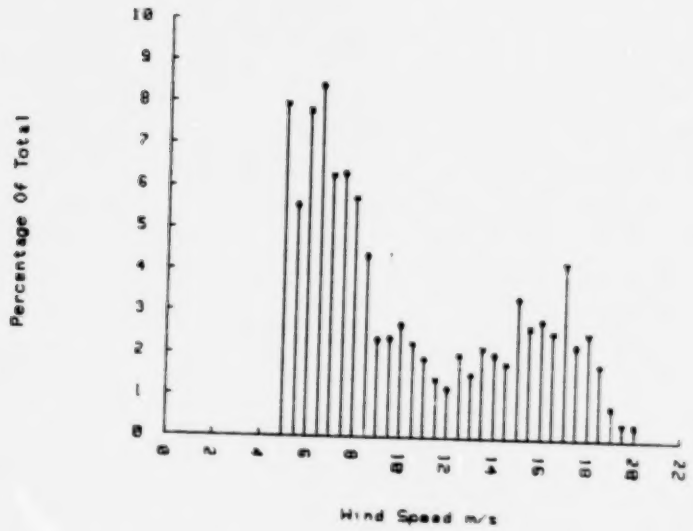
5 MINUTE AVERAGES BINNED



Bin Number	Bin Count	% Total
5	911	7.3989
5.5	732	5.9387
6	888	7.2043
6.5	1021	8.2833
7	892	7.2367
7.5	763	6.1982
8	601	4.8759
8.5	529	4.2917
9	359	2.9125
9.5	294	2.3852
10	319	2.588
10.5	271	2.1986
11	271	2.1986
11.5	187	1.5171
12	181	1.4684
12.5	226	1.8335
13	222	1.8011
13.5	273	2.2148
14	271	2.1986
14.5	267	2.1662
15	336	2.7259
15.5	312	2.5312
16	388	3.1478
16.5	388	3.1478
17	347	2.8152
17.5	334	2.7097
18	286	2.3203
18.5	200	1.6075
19	134	1.0871
19.5	70	.5679
20	45	.3651

Wind Measurement Study
Energy Intensity = 1707.62213345

15 MINUTE AVERAGES BINNED



Bin Number	Bin Count	% Total
5	326	7.9532
5.5	228	5.5623
6	320	7.8068
6.5	344	8.3923
7	257	6.2698
7.5	259	6.3186
8	235	5.7331
8.5	179	4.3669
9	96	2.342
9.5	98	2.3908
10	111	2.708
10.5	93	2.2688
11	78	1.9029
11.5	58	1.415
12	49	1.1954
12.5	82	2.0005
13	63	1.537
13.5	89	2.1713
14	83	2.0249
14.5	74	1.8053
15	138	3.3667
15.5	110	2.6836
16	117	2.8544
16.5	105	2.5616
17	173	4.2205
17.5	92	2.2444
18	104	2.5372
18.5	74	1.8053
19	33	.8051
19.5	16	.3903
20	15	.3659

APPENDIX E. ENERGY AVAILABILITY

In addition to the histograms, calculations were also made on the data to provide a dimensionless energy availability figure for each of the histograms as well as a Rayleigh distribution using the average wind speed.

Total energy available on a site is equal to the sum of individual time periods times the power available for those individual time periods. Power available is proportional to velocity cubed. Energy availability is simply the cube of the wind speed times the frequency of occurrence of that wind speed or

$$\sum_{i=1}^{40} \frac{(BN_i)^3(BC_i)}{\sum_{i=1}^{40} BC_i}$$

where BN is bin number in m/s and BC is bin count (frequency of occurrence).

The energy availability for the binned data is:

Data set	Total energy availability vs. 1 s	WECS energy availability vs. 1 s
Binned 1 s	1.000	1.000
10th data point	0.992	0.993
60th data point	0.997	0.999
300th data point	0.988	0.993
900th data point	0.998	0.967
10-s average	0.988	1.021
1-min average	0.966	1.033
5-min average	0.953	1.044
15-min average	0.956	1.040
Rayleigh distribution U_{avg} - 7.6 m/s	0.635	

APPENDIX F. TURBULENCE CALCULATIONS

Turbulence Calculations

Wind Histogram Study (Mean Wind Speed 3.1 m/s)

Time Period Covered
12:03:54 14OCT84 TO 13:00:00 14OCT84

Turbulence Calculations

1) Using the 1 second data samples = .19111
2) Using every 10th point = .18795
3) Using every 60th point = .20161

Standard Deviation Calculations

1) Using the 1 second data samples = .54708
2) Using every 10th point = .56753
3) Using every 60th point = .61084

Mean Wind Speeds For The Data Sets

1) Using the 1 second data samples = 3.02164489311
2) Using every 10th point = 3.02857142857
3) Using every 60th point = 3.08392857143

Wind Histogram Study (Mean Wind Speed 3.5 m/s)

Time Period Covered
08:24:03 24FEB85 TO 09:24:03 24FEB85

Turbulence Calculations

1) Using the 1 second data samples = .15045
2) Using every 10th point = .15434
3) Using every 60th point = .19158

Standard Deviation Calculations

1) Using the 1 second data samples = .52431
2) Using every 10th point = .53461
3) Using every 60th point = .6495

Mean Wind Speeds For The Data Sets

1) Using the 1 second data samples = 3.48595614765
2) Using every 10th point = 3.47333333333
3) Using every 60th point = 3.44666666667

Wind Histogram Study (Mean Wind Speed 3.8 m/s)

Time Period Covered
03:02:05 04FEB85 TO 04:00:00 04FEB85

Turbulence Calculations

1) Using the 1 second data samples = .1326
2) Using every 10th point = .13169
3) Using every 60th point = .16187

Standard Deviation Calculations

1) Using the 1 second data samples = .51234
2) Using every 10th point = .50534
3) Using every 60th point = .6098

Mean Wind Speeds For The Data Sets

1) Using the 1 second data samples = 3.86475834292
2) Using every 10th point = 3.84841498559
3) Using every 60th point = 3.83333333333

Wind Histogram Study (Mean Wind Speed 3.9 m/s)

Time Period Covered
15:00:34 20DEC84 TO 16:00:34 20DEC84

Turbulence Calculations

1) Using the 1 second data samples = .27361
2) Using every 10th point = .27774
3) Using every 60th point = .25919

Standard Deviation Calculations

1) Using the 1 second data samples = 1.0781
2) Using every 10th point = 1.0884
3) Using every 60th point = 1.0144

Mean Wind Speeds For The Data Sets

1) Using the 1 second data samples = 3.94125177809
2) Using every 10th point = 3.92991452991
3) Using every 60th point = 3.98103448276

Wind Histogram Study (Mean Wind Speed 4.4 m/s)

Time Period Covered
11:37:39 19DEC84 TO 12:38:00 19DEC84

Turbulence Calculations

1) Using the 1 second data samples = .19221
2) Using every 10th point = .19418
3) Using every 60th point = .19642

Standard Deviation Calculations

1) Using the 1 second data samples = .82972
2) Using every 10th point = .83632
3) Using every 60th point = .86296

Mean Wind Speeds For The Data Sets

1) Using the 1 second data samples = 4.3180137931
2) Using every 10th point = 4.31878453039
3) Using every 60th point = 4.46666666667

Wind Histogram Study (Mean Wind Speed 5.8 m/s)

Time Period Covered
14:12:46 18DEC84 TO 15:12:46 18DEC84

Turbulence Calculations

1) Using the 1 second data samples = .15398
2) Using every 10th point = .15759
3) Using every 60th point = .17356

Standard Deviation Calculations

1) Using the 1 second data samples = .90219
2) Using every 10th point = .9179
3) Using every 60th point = 1.0007

Mean Wind Speeds For The Data Sets

1) Using the 1 second data samples = 5.86089975007
2) Using every 10th point = 5.84083333333
3) Using every 60th point = 5.86166666667

Wind Histogram Study (Mean Wind Speed 8.0 m/s)

Time Period Covered
14:09:02 07FEB85 TO 15:09:02 07FEB85

Turbulence Calculations

1) Using the 1 second data samples = .19069
2) Using every 10th point = .19111
3) Using every 60th point = .18646

Standard Deviation Calculations

1) Using the 1 second data samples = 1.5264
2) Using every 10th point = 1.5371
3) Using every 60th point = 1.4621

Mean Wind Speeds For The Data Sets

1) Using the 1 second data samples = 8.0078111588
2) Using every 10th point = 8.07768240343
3) Using every 60th point = 8.04736842105

Wind Histogram Study (Mean Wind Speed 8.4 m/s)

Time Period Covered
09:49:28 08FEB85 TO 10:30:00 08FEB85

Turbulence Calculations

1) Using the 1 second data samples = .11933
2) Using every 10th point = .12338
3) Using every 60th point = .15525

Standard Deviation Calculations

1) Using the 1 second data samples = 1.0016
2) Using every 10th point = 1.0318
3) Using every 60th point = 1.2535

Mean Wind Speeds For The Data Sets

1) Using the 1 second data samples = 8.39750976563
2) Using every 10th point = 8.40343137255
3) Using every 60th point = 8.31176470588

Wind Histogram Study (Mean Wind Speed 10.3 m/s)

Time Period Covered
23:04:07 20DEC84 TO 00:00:01 21DEC84

Turbulence Calculations

1) Using the 1 second data samples	=	.14486
2) Using every 10th point	=	.14191
3) Using every 60th point	=	.15448

Standard Deviation Calculations

1) Using the 1 second data samples	=	1.4895
2) Using every 10th point	=	1.4532
3) Using every 60th point	=	1.5697

Mean Wind Speeds For The Data Sets

1) Using the 1 second data samples	=	10.2852757079
2) Using every 10th point	=	10.2707462687
3) Using every 60th point	=	10.3454545455

Wind Histogram Study (Mean Wind Speed 11.8 m/s)

Time Period Covered
07:02:00 05FEB85 TO 08:00:00 05FEB85

Turbulence Calculations

1) Using the 1 second data samples	=	.17019
2) Using every 10th point	=	.17399
3) Using every 60th point	=	.18705

Standard Deviation Calculations

1) Using the 1 second data samples	=	1.9994
2) Using every 10th point	=	2.0512
3) Using every 60th point	=	2.1961

Mean Wind Speeds For The Data Sets

1) Using the 1 second data samples	=	11.7512923607
2) Using every 10th point	=	11.8229885057
3) Using every 60th point	=	11.9431034483

Wind Histogram Study (Mean Wind Speed 13.4 m/s)

Time Period Covered
01:02:21 25FEB85 TO 02:00:00 25FEB85

Turbulence Calculations

1) Using the 1 second data samples = .14464
2) Using every 10th point = .14902
3) Using every 60th point = .16166

Standard Deviation Calculations

1) Using the 1 second data samples = 1.9308
2) Using every 10th point = 1.9885
3) Using every 60th point = 2.1426

Mean Wind Speeds For The Data Sets

1) Using the 1 second data samples = 13.3521965318
2) Using every 10th point = 13.3826589595
3) Using every 60th point = 13.4859649123